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Wind erosion susceptibility of European soils

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ABSTRACT

The EU Thematic Strategy for Soil Protection identified soil degradation caused by erosion as one of the major threats to European soils. A thorough literature review revealed important gaps in research on soil erosion processes in Europe. This is particularly true for wind erosion processes. The current state of the art in erosion research lacks knowledge about where and when wind erosion occurs in Europe, and the intensity of erosion that poses a threat to agricultural productivity. To gain a better understanding of the geographical distribution of wind erosion processes in Europe, we propose an integrated mapping approach to estimate soil susceptibility to wind erosion. The wind-erodible fraction of soil (EF) is one of the key parameters for estimating the susceptibility of soil to wind erosion. It was computed for 18,730 geo-referenced topsoil samples (from the Land Use/Land Cover Area frame statistical Survey (LUCAS) dataset). Our predication of the spatial distribution of the EF and a soil surface crust index drew on a series of related but independent covariates, using a digital soil mapping approach (Cubist-rule-based model to calculate the regression, and Multilevel B-Splines to spatially interpolate the Cubist residuals). The spatial interpolation showed a good performance with an overall R^2 of 0.89 (in fitting). We observed the spatial patterns of the soils' susceptibility to wind erosion, in line with the state of the art in the literature. We used regional observations in Lower Saxony and Hungary to ensure the applicability of our approach. These regional control areas showed encouraging results, and indicated that the proposed map may be suitable for national and regional investigations of spatial variability and analyses of soil susceptibility to wind erosion.

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1. Introduction

Wind erosion is a widespread phenomenon causing serious soil degradation in arid and semi-arid regions (FAO, 1960; Wolfe and Nickling, 1993). In its more severe forms it can constitutes a threat to cropping and contributes to the degradation of a sustainable cropping agriculture (Lyles, 1975). The wind induced movement of soil occurs when three environmental conditions coincide: i) the wind is strong enough to mobilize soil particles, ii) the characteristics of the soil make it susceptible to wind erosion (soil texture, organic matter and moisture content) and iii) the surface is mostly devoid of vegetation, stones or snow (Bagnold, 1941; Nordstrom and Hotta, 2004; Shao, 2008).

Wind erosion has always occurred as a natural land-forming process (Livingstone and Warren, 1996) but, today, the geomorphic effects of wind are locally accelerated by anthropogenic pressures (e.g. leaving cultivated lands fallow for extended periods of time, overgrazing rangeland pastures and, to a lesser extent, over-harvesting vegetation (Leys, 1999)).

Land degradation due to wind erosion is also an European phenomenon (Warren, 2003) which locally affects the semi-arid areas of the Mediterranean region (Gomes et al., 2003; Lopez et al., 1998; Moreno Brotons et al., 2009) as well as the temperate climate areas of the northern European countries (Bärring et al., 2003; De Ploey, 1986; Eppink and Spaan, 1989; Goossens et al., 2001). According to the EU Thematic Strategy for Soil Protection (European Commission, 2006), an estimated 42 million hectares are affected by wind erosion in Europe. However, the latest investigations within the framework of EU projects (Wind Erosion on European Light Soils (WEELS)) and Wind Erosion and Loss of Soil Nutrients in Semi-Arid Spain (WELSONS; Warren, 2003) suggest that the areas potentially affected by wind erosion may be more widespread than previously reported by the European Environment Agency (EEA, 1998). Field observations and measurements found that the areas that the European Environment Agency reported as being only slightly affected by wind erosion (EEA, 1998) have actually undergone severe erosion (Böhner et al., 2003; Riksen and De Graaff, 2001). These field research findings reveal that the European Environment Agency (EEA, 1998) currently has an incomplete picture about the occurrence and scope of wind erosion in Europe. This could lead to incorrect decision making by national and European institutions in seeking to mitigate wind erosion. To fulfil the goal of the EU Thematic Strategy for Soil Protection (European Commission, 2006), research must aim to better understand where and under which conditions land degradation by wind erosion is most likely to occur. The methodologies that are applied must be harmonised in order to effectively locate the wind erodible areas in Europe.

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Table 1
List of environmental covariates used for the spatial interpolation.

Parameter	Data source	Spatial resolution
Land use and land cover data	International Geosphere–Biosphere Programme	1 km
Monthly temperatures (min & max)	WorldClim — Global Climate Data v 1.4	1 km
Monthly precipitations	WorldClim — Global Climate Data v 1.4	1 km
Satellite imagery		
Red, blue, green, near infrared (NIR) and middle infrared (MIF) bands	NASA — Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m
Principal Component Analysis of the satellite imagery	NASA — Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m
Vegetation indices: Enhanced Vegetation Index (EVI) & Normalized Differenced Vegetation Index (NDVI)	NASA — Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m
Principal Component Analysis of the Enhanced Vegetation Index & Normalized Differenced Vegetation Index	NASA — Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m
Digital Elevation Model (DEM)	NASA SRTM Digital Elevation Database v4	90 m
Multi-resolution valley bottom flatness index	DEM derivative	90 m
Slope gradient	DEM derivative	90 m
Drainage network	DEM derivative	90 m
Altitude above channel network	DEM derivative	90 m
Down-slope distance	DEM derivative	90 m
Latitude & latitude	Coordinate system (ETRS_1989_LAEA)	–

This study provided an assessment of the susceptibility of European soils to wind erosion. It is a key parameter of integrated modelling for the spatial assessment of the wind erosion risk (Hagen, 2004). The erodibility of European soil was estimated as the wind-erodible fraction, a simplification of Chepil's (1941) work (Woodruff and Siddoway, 1965). Soil characteristics were obtained from the first topsoil survey of the whole European Union (Tóth et al., 2013). The assessment presented in this paper is part of a preliminary investigation that aims to further investigate the patterns of soil susceptibility to wind erosion across Europe, and to research the occurrence of wind erosion at regional and European scales.

2. Material and methods

2.1. Study area

The study area was made up of 25 member states of the European Union. Bulgaria, Romania and Croatia were excluded from the study because data from their LUCAS soil samples were not available. The total land surface is about 4 million km^2, providing living space for a population of about 470 million (Eurostat, 2012). According to Eurostat (2012) two-fifths (about 1.55 million km^2) of the total land area was used for agricultural purposes in 2007.

2.2. Soil database

Soil information for the 25 EU member states was acquired from the Land Use/Land Cover Area frame statistical Survey (LUCAS) database, which provided data from 2009 onwards. This was combined with a topsoil assessment component ('LUCAS-Topsoil' — Tóth et al., 2013). LUCAS-Topsoil comprises the first harmonised and comparable dataset on soil at the European level. We used a merged database that contained 19,967 geo-referenced samples (each of 0.5 kg of topsoil, collected at a depth of 0–20 cm), which was selected from a subset of 200,000 potential LUCAS sampling sites. Budgetary constraints did not allow for a broader sampling exercise. Geostatistical techniques were employed to sample representative points (Tóth et al., 2013). All 19,967 samples were analysed for their coarse fragment percentage, particle size distribution (% clay, silt and sand content), pH value (in $CaCl_2$ and H_2O), organic carbon content (g kg^{-1}), carbonate content (g kg^{-1}), phosphorous content (mg kg^{-1}), total nitrogen content (g kg^{-1}), extractable potassium content (mg kg^{-1}), cation exchange capacity (cmol + kg^{-1}) and multispectral properties.

2.3. Computation of the erodible fraction (EF)

In the early 1950s, the combination of soil sieving and wind tunnel experiments provided evidence of the relationship between soil loss by wind and the characteristics of the soil surface (Chepil, 1950; Chepil and Woodruff, 1954). The field observations revealed that aggregates that were larger than 0.84 mm in diameter were non-erodible under test conditions. As a result of these findings, the proportion of topsoil aggregates < 0.84 mm in diameter (i.e. the wind-erodible fraction (EF) of the soil) became a commonly accepted and widely applied measure of soil erodibility by wind (Colazo and Buschiazzo, 2010; Hevia et al., 2007; Woodruff and Siddoway, 1965), which has been widely employed ever since in prediction models (Chepil et al., 1962; Woodruff and Siddoway, 1965). Fryrear et al. (1994) developed a multiple regression equation for computing the erodible fraction of soils based on the soil's texture and chemical properties (Fryrear et al., 2000):

$$EF = \frac{29.09 + 0.31S_a + 0.17S_i + 0.33S_c - 2.59OM - 0.95CaCO_3}{100} \quad (1)$$

where all variables are expressed as a percentage. S_a is the soil sand content, S_i is the soil silt content, S_c is the ratio of sand to clay

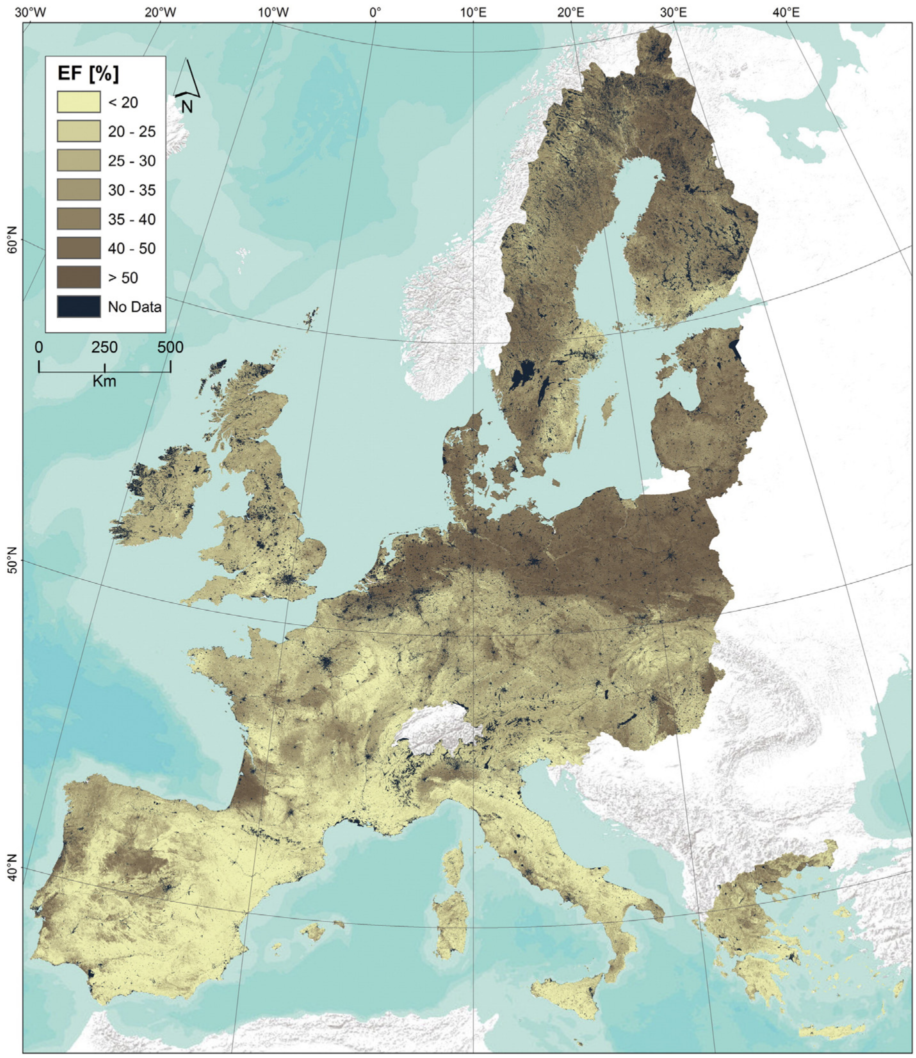

Fig. 1. Map of wind erosion susceptibility of European soils (500 m spatial resolution) based on the estimation of the wind-erodible fraction of soil (EF) (Chepil, 1941; Fryrear et al., 2000). The map was obtained by interpolating the EF values (Chepil, 1941; Fryrear et al., 2000) calculated for 18,730 geo-referenced topsoil samples (Land Use/Land Cover Area frame statistical Survey — LUCAS dataset). For the interpolation, a Cubist-rule-based model was used for the regression, and a Multilevel B-Splines for the spatial interpolation of the Cubist residuals. The geographical extent of this study includes 25 member states of the European Union. Bulgaria, Croatia and Romania were not included as the LUCAS-Topsoil database currently does not include them. Non-erodible surfaces (such as lakes, glaciers, bare rocks and urban areas) were described as No Data.

contents, OM is the organic matter content and $CaCO_3$ is the calcium carbonate content.

The study carried out by Fryrear et al. (1994) calculated an R^2 of 0.67, leaving 33% of the erodible fraction variability unexplained. The recent applications of the equation in Europe and Argentina, however, have revealed certain limits to its transferability (López et al., 2007). López et al. (2007) stated that the model proposed by Fryrear et al. (1994) did not fit with the measured EF values. This was attributed to the high $CaCO_3$ contents of Spanish soils and the low sand/clay ratios and high organic matter contents of some Argentinean soils. Despite these limitations, the equation constitutes one of the most robust and widely tested equations defined in the literature to assess the intrinsic susceptibility of soil to wind erosion. Therefore, we calculated the wind-erodible fraction of the soil by using Eq. (1) and the LUCAS soil data. This enabled us to delineate the susceptibility of European soils to wind erosion into spatial patterns.

The LUCAS dataset contains 19,967 sample points. A set of 1,237 sample points (mainly organic soils) was excluded from the dataset. Before applying Eq. (1), some of the remaining 18,730 sample points were modified as following: For the soil samples with an organic matter content above 4.79% and a $CaCO_3$ content above 25.2%, the upper limits of 4.79% (6209 samples; mean = 10%, $\sigma = 5.9\%$) and 25.2% (1710 samples; mean = 41%, $\sigma = 13.1\%$) were applied. Minimum (5%, n = 1359) and maximum (70%, n = 99) threshold values were imposed upon the calculated erodible fraction values where the physical characteristics of the sampling points were outside the equation's validation limits. Finally, the erodible fraction values were further adjusted to consider the rock fraction that is not erodible (Zobeck, 1991). This was accomplished by subtracting the average surface stone cover (%) reported in the LUCAS dataset. Non-erodible surface (such as lakes, glaciers, bare rocks and urban areas) were described in the map as 'No Data'.

2.4. Computation of a soil crust index

The impact of raindrops on the soil surface leads to a redistribution of soil particles and creates a soil surface crust (Belnap, 2003). Depending on the soil properties, the surface crust may decrease or increase wind erosion potential (Zobeck, 1991). The soil crust factor (SCF, Fryrear et al., 2000) was employed to estimate the influence of the soil crust occurrence on the wind erosion susceptibility of European soils. This is an empirical relationship which was developed using laboratory wind tunnel tests on the resistance of soil aggregates and crusts to windblown sand of Hagen et al. (1992). According to Fryrear et al. (2000), the soil crust factor was developed by regressing the soil crust

Table 2
Descriptive statistics of the wind-erodible fraction of soil for European countries.

Country	Mean [%]	Maximum	Standard deviation	Coefficient of variation
Austria	27.2	46.5	3.6	13.3
Belgium	32.0	61.2	6.9	21.6
Cyprus	18.5	45.2	5.7	30.7
Czech Republic	30.8	54.5	4.6	14.9
Denmark	41.1	61.4	5.7	13.8
Estonia	38.3	61.6	5.8	15.1
Finland	38.6	67.0	8.0	20.7
France	24.4	60.5	7.5	30.8
Germany	35.0	69.0	10.2	29.2
Greece	23.7	61.3	7.3	30.9
Hungary	30.9	64.9	7.6	24.5
Ireland	27.9	41.7	2.8	10.1
Italy	22.0	52.6	6.0	27.4
Latvia	40.1	62.4	5.2	12.9
Lithuania	39.3	62.5	5.5	14.1
Luxembourg	24.6	37.9	3.1	12.6
Malta	21.8	36.7	4.8	22.0
Netherlands	40.6	67.1	9.8	24.1
Poland	45.2	68.8	8.4	18.5
Portugal	25.5	67.8	9.3	36.6
Slovakia	26.2	53.3	4.6	17.8
Slovenia	23.3	44.6	5.1	22.0
Spain	20.4	58.6	7.6	37.3
Sweden	34.5	63.8	6.2	17.9
United Kingdom	27.7	54.9	4.0	14.6

factor, as determined by the abrasion coefficient, on clay (clay) and organic matter (OM):

$$\mathrm{SCF} = \frac{1}{\left[1 + 0.0066(\mathrm{clay})^2 + 0.21(\mathrm{OM})^2\right]}.$$

For the soil samples with an organic matter content of above 4.79%, an upper cut-off point of 4.79% was applied (6209 samples; mean = 10%, σ = 5.9%). With regard to the clay content, an upper limit of 39.3% (1481 samples; mean = 48.2%; σ = 7.44) and a lower limit of 4.9% was used (1428; mean = 2.47%; σ = 0.63).

2.5. Spatial prediction of the wind-erodible fraction and surface crust factor

The digital soil mapping approach was employed to calculate the wind-erodible fraction of soil and soil surface crusting factor by deriving its distribution from a series of related but independent covariates (Goovaerts, 1998). This approach aims to establish a statistical relationship between the property to be calculated and a set of spatially exhaustive covariates. Once this relationship is found, the dependent property is estimated everywhere within the geographic frame of interest (Goovaerts, 1998).

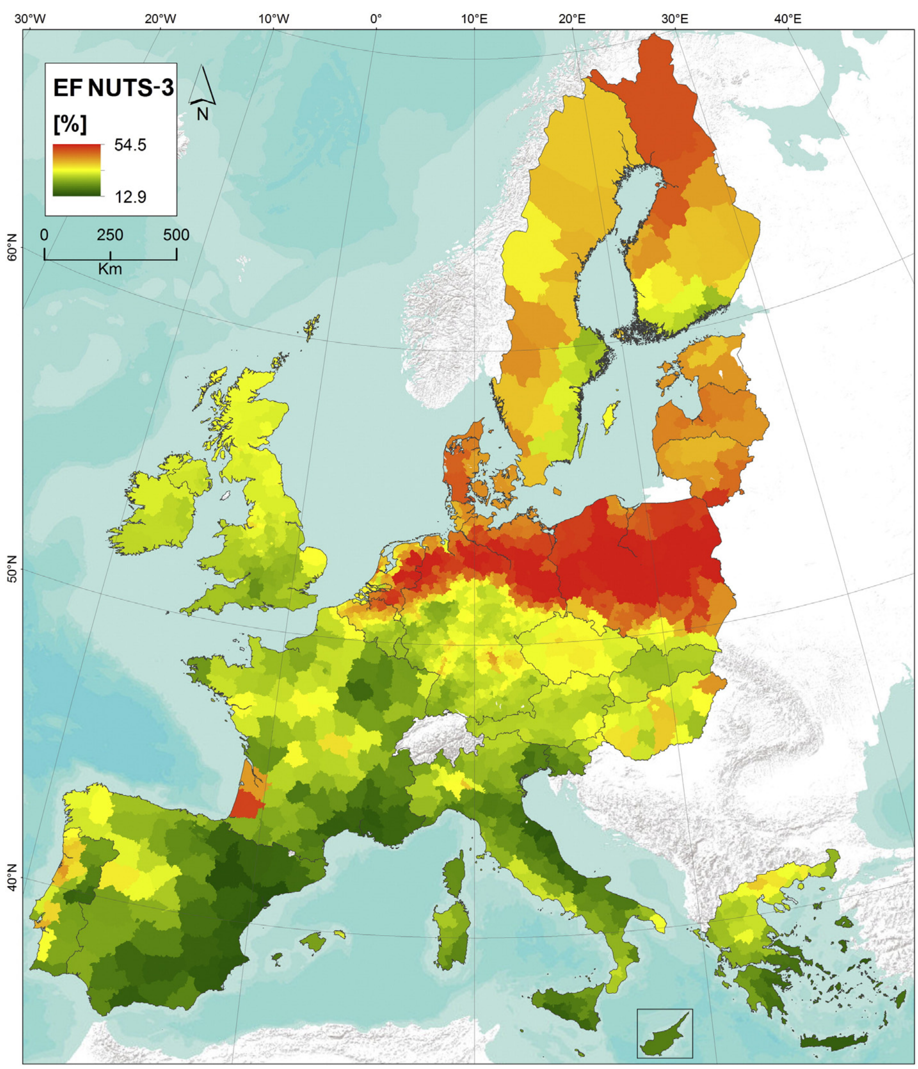

Fig. 2. The average wind-erodible fraction of soil (EF), according to European Union NUTS-3 administrative units.

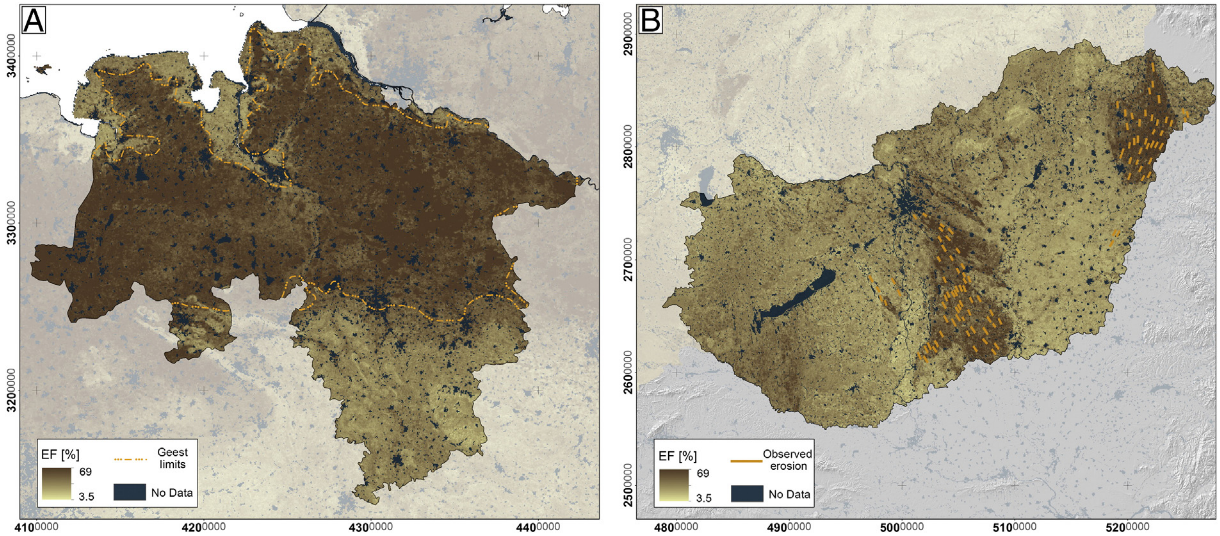

Fig. 3. Comparison of the predicted wind erosion susceptibility of soil (background raster image) with regional observations (represented with yellowish lines). a) The Geest area in Lower Saxony. This area mainly consists of glacial moraines and sand plains, forming light sandy soils largely endangered by wind erosion (Capelle, 1990; Gross and Schäfer, 2004, among others). b) Area affected by wind erosion in Hungary according to Stefanovits and Várallyay (1992).

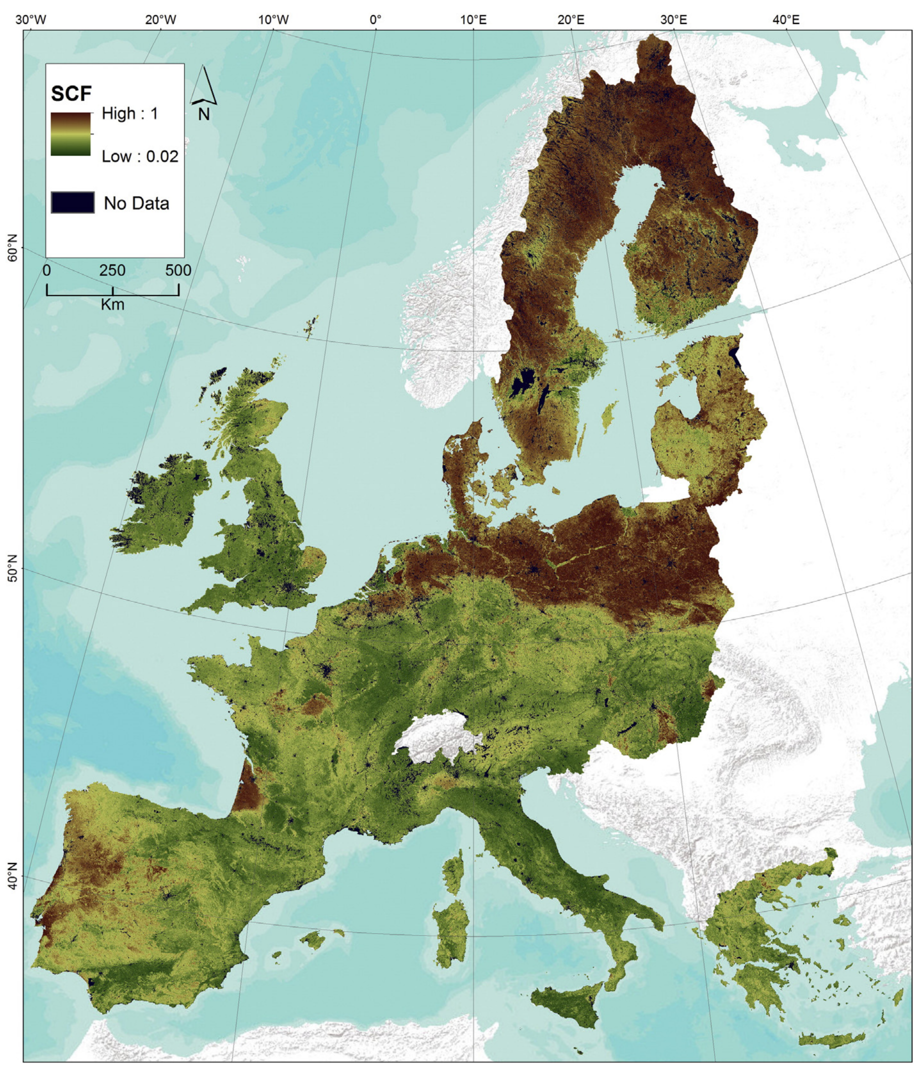

Fig. 4. Map of the soil crust factor of European soils (500 m spatial resolution). Based on the work of Fryrear et al. (2000) and Hagen et al. (1992).

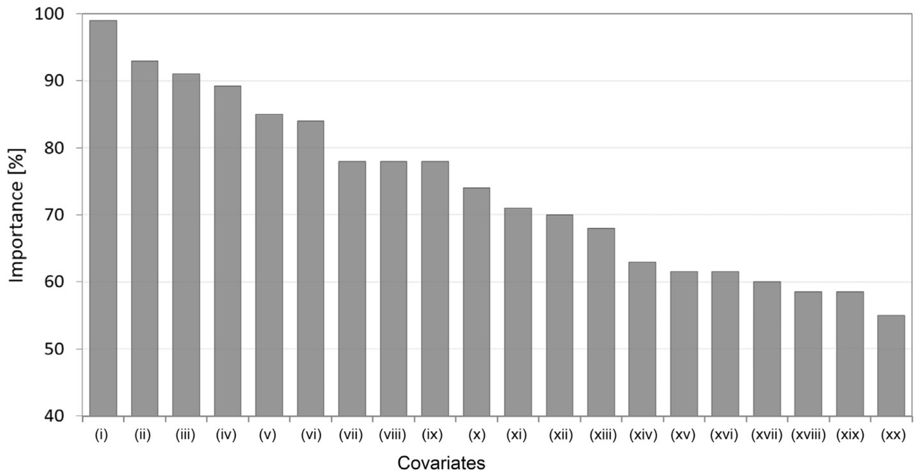

Fig. 5. The twenty most important covariates and their relative importance in the application of Cubist/MBS model for wind-erodible fraction of soil (EF) prediction. (i) Latitude; (ii) altitude above channel network; (iii) elevation; (iv) PCAb1 of Red band; (v) PCAb3 of NIR band; (vi) PCAb1 MIR; (vii) PCAb3 MIR; (viii) MIR; (ix) PCAb1 EVI; (x) PCAb5 MIR; (xi) drainage network; (xii) land use and land cover; (xiii) PCAb2 NIR; (xiv) longitude; (xv) multi-resolution valley bottom flatness index; (xvi) slope gradient; (xvii) PCAb2 Red; (xviii) NIR; (xix) PCAb4 MIR; and (xx) PCAb2 MIR.

In our study, the value of the wind-erodible fraction of soil and soil surface crusting factor that were calculated for the LUCAS points were interpolated using a series of environmental descriptors (covariates), in order to map its spatial distribution. Regression residuals were then spatially interpolated according to their covariance function. In general, this kind of model can be described as:

$$\hat{z}(\mathbf{s}_0) = \hat{m}(\mathbf{s}_0) + \hat{\varepsilon}(\mathbf{s}_0) \tag{2}$$

where $\hat{m}(\mathbf{s}_0)$ represents the deterministic part fitted by the regression model and $\hat{\varepsilon}(\mathbf{s}_0)$ represents the interpolated residuals.

The two components were then summed to obtain the final estimation of the erodible fraction. This hybrid approach was performed using the Cubist-rule-based model (Quinlan, 1992) to carry out the regression, and Multilevel B-Splines (MBS; Lee et al., 1997) to spatially interpolate the Cubist residuals. The Cubist model was fitted by k-fold cross validation in order to evaluate the best combination of committees and neighbours.

In terms of accuracy and lack of bias, the Multilevel B-Splines algorithm performs as well as the kriging. It is also computationally faster and allows for an easy estimation of the smoothness of the interpolated field. In our case, an optimal smoothness was estimated using Generalized Cross Validation (GCV) (Craven and Wahba, 1979) by trading model complexity for prediction error.

Various covariates were considered for the Cubist model (Table 1). Two main types were considered to be the most appropriate: i) Remotely sensed data, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), including vegetation indices (Normalized Differenced Vegetation Index — NDVI, Enhanced Vegetation Index — EVI) and raw band data which were re-projected using Principal Component Analysis (PCA). This data comprised the full cycle of yearly observations of MODIS. ii) Terrain features, derived from the SRTM Digital Elevation Model (Jarvis et al., 2008), including common geomorphometric descriptors (including slope, altitude above channel base level, multi-resolution index of valley bottom flatness).

2.6. Evaluation of the outcomes

A cross validation was carried out to evaluate the performance of the spatial prediction approach. The extremely limited number of studies that report soil erodible fraction estimations (Fryrear et al., 1994) or similar types of soil erodibility by wind assessment (Gross and Schäfer, 2001) did not allow for the application of further validation procedures for the calculated values of soil erodibility. We ensured that our results were consistent with theoretic expectations. Furthermore, we compared our findings with previous studies (Bärring et al., 2003; Eppink and Spaan, 1989; Gross and Schäfer, 2001; Huber et al., 2008; Kertész and Centeri, 2006; Stefanovits and Várallyay, 1992) for the geographical areas where soil susceptibility to wind erosion had been reported (i.e., Geest area of Lower Saxony, Southern Great Plains of Hungary and the Dutch provinces of Groningen and Drenthe).

3. Results and discussions

3.1. Soil susceptibility to wind erosion

We estimated the wind-erodible fraction based on the 15.786 million cells (500 m spatial resolution) into which we subdivided the surface of the 25 EU countries (Fig. 1). The resulting erodible fraction values ranged from 3.6% to 69.0%, with a mean value of 30% (σ 10.6%). According to the erodibility classification proposed by Shiyatyi (1965), which has been adopted for European contexts by López et al. (2007), 81.3% (EF < 40%) and 13.8% (EF ≥ 40% and <50%) of the investigated area are characterised by slight and moderate erodibility, respectively, whereas 4.9% are characterised by high erodibility (EF ≥ 50%). As can be inferred from Fig. 1, the distribution of the spatial wind-erodible fraction patterns suggests a division of the European surface into three regions: i) a north region mostly dominated by the highest EF values, ii) a central eastern region with average EF values interspersed with some high/low spots, and iii) the Mediterranean area, which has mainly low wind-erodible fraction values.

A cross-country comparison of the mean erodible fraction values (Table 2 — National level; Fig. 2 — NUT-3 level (Nomenclature of Territorial Units for Statistics — Eurostat, 2013)) confirms the regional structure. The Mediterranean countries (Cyprus, Spain, Malta and Italy) have the lowest average erodible fraction values (18.5% to 22%). The highest values appear in the areas surrounding the North Sea and the Baltic Sea, with Poland, Denmark, the Netherlands and northern Germany showing average values of above 40%. The higher coefficient of variation values (c_v) in the southern countries (Table 2) confirms the regional pattern. These patterns show a spatial distribution of the soils' erodibility by wind erosion which is clearly distinct from the soil erodibility pattern identified for water erosion (K-factor, Panagos et al., 2014). While this generally applies across Europe, the situation is particularly true for the northern part of central Europe, France and Spain.

The academic literature on soil degradation in Europe identified wind erosion as a major threat to northern Europe (Warren, 2003). This is because the phenomenon has especially significant effects on light sandy soils (Bärring et al., 2003; Eppink and Spaan, 1989; Goossens and Gross, 2002; Riksen and De Graaff, 2001). The sandy soils of northern Europe often show a bimodal grain-size distribution and a secondary maximum in the silt range. Further observations of their erosion susceptibility patterns confirmed that the sandy soils of northern Europe are characterised by a higher susceptibility to wind erosion. Fig. 3, which shows the Geest area of Lower Saxony (Gross and Schäfer, 2004), provides an example of areas that are highly susceptible to wind erosion. As indicated by the wind tunnel experiments of Gross and Schäfer (2001), the region, which mainly consists of glacial moraines and sand plains, is predominantly covered by sandy soils and is thus highly susceptible to wind erosion. Our results reflect regional soil erodibility dynamics very well. In fact, Fig. 3a shows high erodibility values for the Geest areas (an average 48% wind-erodible fraction of soil), intermediate values for the loess at the Geest's southern boundary (38%), and lower values along the coast and the southern area of Lower Saxony (30%). Further proof of the good correlation between our results and the land susceptibility to wind erosion described in the literature (Kertész and Centeri, 2006; Stefanovits and Várallyay, 1992) is reported in Fig. 3b. For Hungary, the figure illustrates the degree to which the areas are affected by wind erosion processes. The findings of Stefanovits and Várallyay (1992) coincide extremely well with our predictions. Further encouraging results were obtained from comparisons with studies carried out in south-east England (Huber et al., 2008) and the Dutch provinces of Groningen and Drenthe (Eppink and Spaan, 1989).

3.2. Soil crust factor

Surface map of soil crust factor (SCF) is shown in Fig. 4. The soil crust factor values range between 0.02 and 1, with an average value of 0.39 ($\sigma = 0.18$). Similar to the wind-erodible fraction (EF), the spatial pattern of soil crust factor shows higher values in the northeast region. The soil crust factor values tend to decrease moving towards the southwest direction. The sandy soils characterizing the glacial deposits of the northern countries (Denmark, Germany, Netherlands, Scandinavia and Baltic area) and the soils with a significant percentage of sand (the north-western Iberian Peninsula, the French region of Limousin and the coastline of Aquitaine along the Atlantic Ocean) are less affected by the formation of a soil surface crust. Here, the soils are more easily eroded by wind as the raindrop-impacted soil surface is aerodynamically smoother than the cloddy surface before the rain (Belnap, 2003; Fryrear et al., 2000). By contrast, the soils with high clay content (e.g., Sicily, Andalicia) led to the formation of a resistant soil surface crust that effectively limits the erosive power of the wind.

3.3. Evaluation of the outcomes

Following the approach described in Section 2.5, the wind-erodible fraction of soil was modelled using a series of environmental descriptors (covariates) and the Cubist model, and by interpolating the Cubist residuals using the Multilevel B-Splines. The Cubist method automatically selects the most informative covariates (Fig. 5). The proposed method was therefore able to predict the distribution of the wind-erodible fraction of soil with a good performance ($R^2 = 0.5$) and an RMSE = 10.1 in a k-fold cross validation. The interpolation by Multilevel B-Splines further increased the prediction performance up to an R^2 of 0.89 (in fitting).

3.4. Data availability

The European maps of the wind-erodible fraction of soil and soil crust factor are available on the European Soil Data Centre (ESDAC) web platform (Panagos et al., 2012). They can be downloaded free of charge in GeoTIFF raster format (http://esdac-catalog.jrc.ec.europa.eu/) in order to encourage further regional and pan-European investigations into spatial variability and analysis of soil susceptibility to wind erosion.

4. Conclusions

The elaboration of the LUCAS-Topsoil data combined with digital soil mapping techniques allowed for the assessment of soil susceptibility to wind erosion at a European scale. This constitutes, to the best of our knowledge, the first comprehensive study of its kind. The accuracy assessment confirmed the good performance of the Cubist method. By interpolating approximately 20,000 wind-erodible fraction values of soil, we reproduced spatial patterns of soil susceptibility to wind erosion in line with the published literature. The distribution of light sandy soils which frequently suffer from degradation due to wind erosion was spatially described and illustrated. In addition, regional observations gave encouraging results with regard to the reliability of the study outcomes and its suitability for local-scale applications. The use of the LUCAS dataset allowed us to take a significant step towards: i) the development of spatial analysis of soil susceptibility to wind erosion, ii) the development of an integrated GIS-based risk assessment of wind erosion at regional and national scales, and iii) the better identification of areas that are susceptible to wind erosion. These insights will help to identify areas that are at risk of wind erosion, and for which conservation measurements such as shelterbelts or windbreaks (Jönsson, 1994) should be considered by decision makers.

5. Ongoing and planned future research

This communication describes research carried out on the susceptibility of European soils to wind erosion. Drawing on these insights, further studies on land susceptibility to wind erosion processes need to be pursued. As the physics of wind erosion is complex, soil as well as atmospheric and land-surface processes must be taken into account in order to assess the wind erosion susceptibility of European soils. Therefore, our ongoing and planned research activities focus on the development of integrated modelling approaches that aim to spatially define i) the EU land surface that is susceptible to wind erosion, and ii) the arable lands that are subject to soil degradation processes. To achieve these objectives, two different modelling approaches are undertaken (a pixel- and an object-oriented model).

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